Augmented Reality Using Ultra-Wideband Radar Imagery

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ABSTRACT

The U.S. Army Research Laboratory (ARL) has been investigating the utility of ultra-wideband (UWB) synthetic aperture radar (SAR) technology for detecting concealed targets in various applications. We have designed and built a vehicle-based, low-frequency UWB SAR radar for proof-of-concept demonstration in detecting obstacles for autonomous navigation, detecting concealed targets (mines, etc.), and mapping internal building structures to locate enemy activity. Although the low-frequency UWB radar technology offers valuable information to complement other technologies due to its penetration capability, it is very difficult to comprehend the radar imagery and correlate the detection list from the radar with the objects in the real world.

Using augmented reality (AR) technology, we can superimpose the information from the radar onto the video image of the real world in real-time. Using this, Soldiers would view the environment and the superimposed graphics (SAR imagery, detection locations, digital map, etc.) via a standard display or a head-mounted display. The superimposed information would be constantly changed and adjusted for every perspective and movement of the user. ARL has been collaborating with ITT Industries to implement an AR system that integrates the video data captured from the real world and the information from the UWB radar. ARL conducted an experiment and demonstrated the real-time geo-registration of the two independent data streams. The integration of the AR sub-system into the radar system is underway. This paper presents the integration of the AR and SAR systems. It shows results that include the real-time embedding of the SAR imagery and other information into the video data stream.

Keywords: augmented reality (AR)**,** ultra-wideband radar (UWB), synthetic aperture radar (SAR).

1. Introduction

The U.S. Army Research Laboratory (ARL) has been investigating the utility of ultra-wideband (UWB) synthetic aperture radar (SAR) technology for detecting concealed targets in various applications. We have designed and built a vehicle-based, low-frequency UWB SAR radar for proof-of-concept demonstrations in detecting obstacles for autonomous navigation, detecting concealed targets (mines, etc.), and mapping internal building structures to locate enemy activity.

Figure 1: The ARL UWB SIRE radar system integrated on the Ford Expedition.

Although the low-frequency UWB radar technology offers valuable information to complement other sensors due to its penetration capability, it is very difficult to comprehend the radar imagery and correlate the detection list from the radar with the objects in the real world. Figure 1 shows the ARL low-frequency radar configured in forward-looking mode. The radar illuminates the scene in front of the vehicle, and generates SAR imagery of the scene and likely target locations as the vehicle moves forward. Figure 2a shows the user's view of the real world from inside the vehicle. Without using any sensor technology, the user depends completely on his (or her) own senses to detect the potential threats in front of the vehicle. On the other hand, Figure 2b shows an example of the displayed SAR imagery of the scene that might help the user to identify the potential threats. The problem is that even though the information from the display of Figure 2b might be valuable, it is very difficult for the user to comprehend the radar imagery and correlate the information between the radar image/detection location and the

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14. ABSTRACT
The U.S. Army Research Laboratory (ARL) has been investigating the utility of ultra-wideband (UWB) synthetic aperture radar (SAR) technology for detecting concealed targets in various applications. We have designed and built a vehicle-based, low-frequency UWB SAR radar for proof-of-concept demonstration in detecting obstacles for autonomous navigation, detecting concealed targets (mines, etc.), and mapping internal building structures to locate enemy activity. Although the low-frequency UWB radar technology offers valuable information to complement other technologies due to its penetration capability, it is very difficult to comprehend the radar imagery and correlate the detection list from the radar with the objects in the real world. Using augmented reality (AR) technology, we can superimpose the information from the radar onto the video image of the real world in real-time. Using this, Soldiers would view the environment and the superimposed graphics (SAR imagery, detection locations, digital map, etc.) via a standard display or a head-mounted display. The superimposed information would be constantly changed and adjusted for every perspective and movement of the user. ARL has been collaborating with ITT Industries to implement an AR system that integrates the video data captured from the real world and the information from the UWB radar. ARL conducted an experiment and demonstrated the real-time geo-registration of the two independent data streams. The integration of the AR sub-system into the radar system is underway. This paper presents the integration of the AR and SAR systems. It shows results that include the real-time embedding of the SAR imagery and other information into the video data stream.

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objects of the real scene. This conventional user interface might not be acceptable for two reasons. First, the user needs to focus in and directly interact with the real world where the reaction time is critical. Second, the decision based on both visible and SAR information is very important. Although the low-frequency UWB radar might be able to detect targets that are not visible to human eyes, it also detects other targets that the user considers as non-threat targets, such as trees, light poles, fire hydrants, etc. Thus, it is best to present the integrated information from both worlds (real world and sensor world) to the radar operator.

Figure 2a: User's view of the real-world from inside the vehicle.

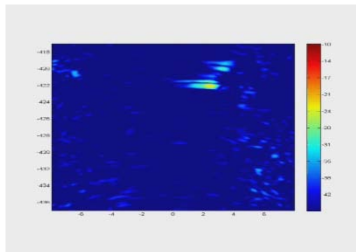


Figure 2b: SAR image of a scene is displayed on a computer screen.

The emerging augmented reality (AR) technology addresses this problem. This technology combines the best features from both domains: virtual reality (VR) and the real world. In VR technology, the user is completely immersed in the computer world. The user can navigate in the virtual world using information from the computer databases and other input/output devices. Although VR is very useful in environments such as simulations and trainings, in many other applications the user needs to interact with the real world. AR technology allows the user to stay in the real world, but extends it with useful information from the computer databases and other sensors to increase the user's perception. In the simplest form, the user sees the world through a video camera and a display. An AR system would overlay the information from the computer database and sensors onto the live video stream. The information from both worlds is geo-registered and displayed using the same coordinate system. The registration is performed and updated in real-time with every user's movement and perspective.

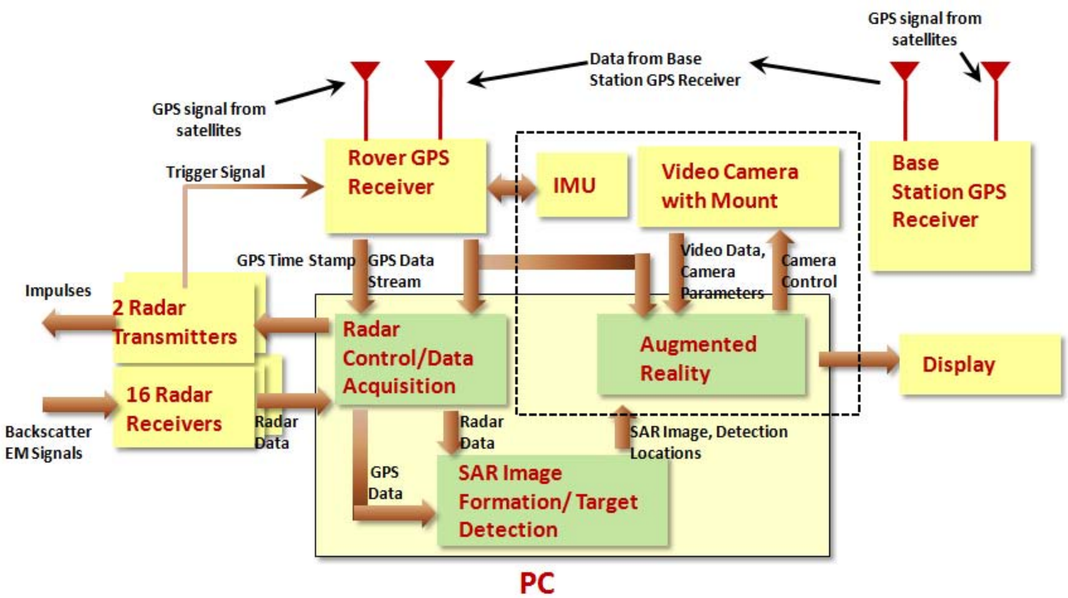


Figure 3: Major components of the radar system and AR subsystem.

Using the AR technology, we are exploring the approaches of incorporating the information from the low-frequency UWB radar sensor into the live video display of the scene to assist the radar operator to determine the real threats ahead. Section 2 gives an overview of the radar system, the SAR imaging geometry, and the imaging process. The SAR imagery generated by the radar is completely geo-referenced using the Universal Transverse Mercator (UTM) coordinate system. The integration of the AR subsystem and the radar into a single system is underway and is described in section 3. Finally, the paper shows the result from an AR experiment to demonstrate the real-time registration and display of SAR information onto the live video stream.

2. Overview of the ARL UWB radar hardware and SAR image formation

In-depth detail of the SIRE radar system is discussed in [1]. Figure 3 shows the major components of the radar. The components inside the dashed rectangle are additional components from the AR subsystem. The radar is a UWB, time-domain, impulse-based system. Down-range resolution is provided by the bandwidth of the transmitted monocycle pulse, which occupies 300–3000 MHz. Sixteen identical Vivaldi-Notch receiving antennas are used to provide a physical aperture for the forward-looking mode. Two TEM horn transmitting antennas are located at both ends of the receiving array. The ARL UWB radar employs a stationary GPS receiver (located at some distance from the radar) and a rover GPS receiver (attached to the radar antenna frame) to provide the radar geo-referenced coordinates that are necessary for the image formation algorithm. Both receiver units are configured for real-time kinematic (RTK) mode. The stationary GPS receiver sends the correction information to the rover GPS receiver via a radio link to provide an accuracy of less than 2 cm. The radar operation is controlled by a graphical-user-interface (GUI)-based PC workstation with high-speed data acquisition hardware to acquire the digitized radar data. All of these radar components are packaged onto a mobile test-bed using a modified Ford Expedition shown in Figure 1.

Figure 4 shows the radar data imaging geometry in the forward-looking mode. The range coverage for this implementation is designed to have 26 m of range swath available, with a starting range of 8 m in front of the receiving antenna array and an ending range of 34 m. The radar is a wide bandwidth impulse-based UWB system. The downrange resolution is a function of the signal bandwidth $(\Delta_r = \frac{c}{2B})$, where c is the speed of light and B is the bandwidth of the radar signal. ARL has developed a suite of signal processing and image formation algorithms to remove noise and artifacts from radar data, and provide an SAR image with resolution in both down-range and cross-range direction. Figure 5 shows the overall block diagram of the signal processing and image formation steps. The PC acquires the digitized radar data. Three signal processing steps (self-interference extraction, forward-motion correction, and frequency sub-banding) are then applied to remove noise and artifacts embedded in the radar data. Finally, the image formation algorithm is applied to generate SAR imagery. Detailed descriptions of the signal processing and image formation algorithms are included in [2] and [3]. It is important to note here is that every pixel in the resulting SAR image is geo-referenced using the UTM coordinate system provided by the two GPS units operated in RTK mode. Thus, any information extracted from the SAR image (such as likely target locations) is also geo-referenced.

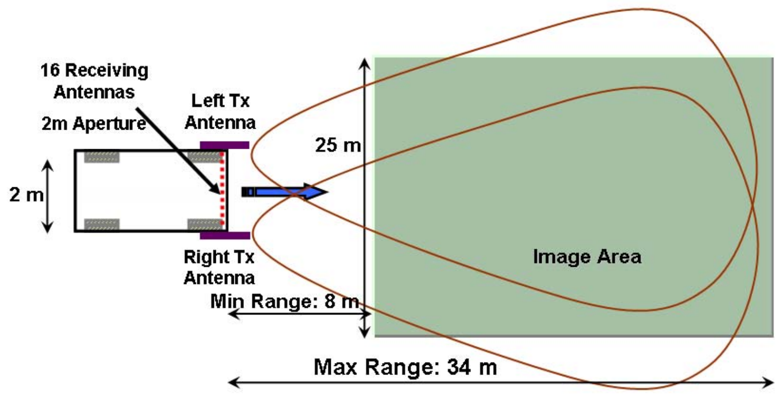


Figure 4: The ARL UWB SIRE radar imaging geometry in forward-looking mode.

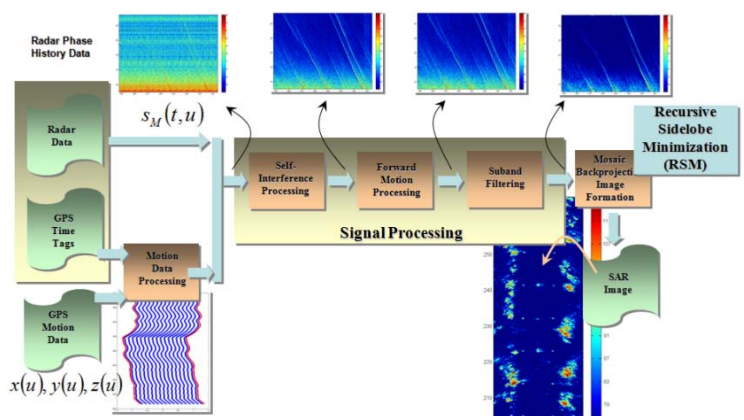
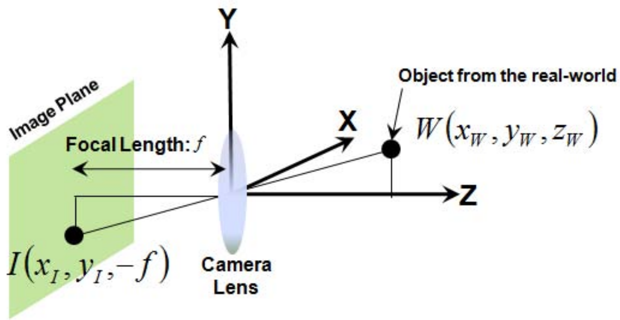


Figure 5: Signal processing and SAR image formation.

3. Integration of the augmented reality into the UWB radar

Figure 6 shows the basic projection concept that AR technology employs to geo-reference objects from a scene of the real world. The figure shows a camera lens that is located at the center of the geo-reference coordinate system. In this



figure, the Z-axis of the coordinate system is aligned with the axis of the camera lens. A point object *W* from the scene with 3D coordinates (x_W, y_W, z_W) is projected by the camera lens onto a point *I* of coordinates $(x_I, y_I, -f)$ in the image plane. The value *f* is the focal length of the camera. This is a projection from the 3D world onto a 2D plane. The projection operation can be described as

$$I = C \cdot W, \tag{1}$$

where *I* and *W* are 3x1 vectors, and *C* is a 3x3 camera projection matrix.

Equation (1) can also be written as

$$z_W \begin{bmatrix} x_I \\ y_I \\ 1 \end{bmatrix} = \begin{bmatrix} -f & 0 & 0 \\ 0 & -f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_W \\ y_W \\ z_W \end{bmatrix}. \tag{2}$$

In practice, the camera is not located at the center of the geo-referenced coordinate system, and the axis of the camera is not aligned with any axis of the coordinate system. Equation (1) becomes

$$I = C \cdot R \cdot (W - T), \tag{3}$$

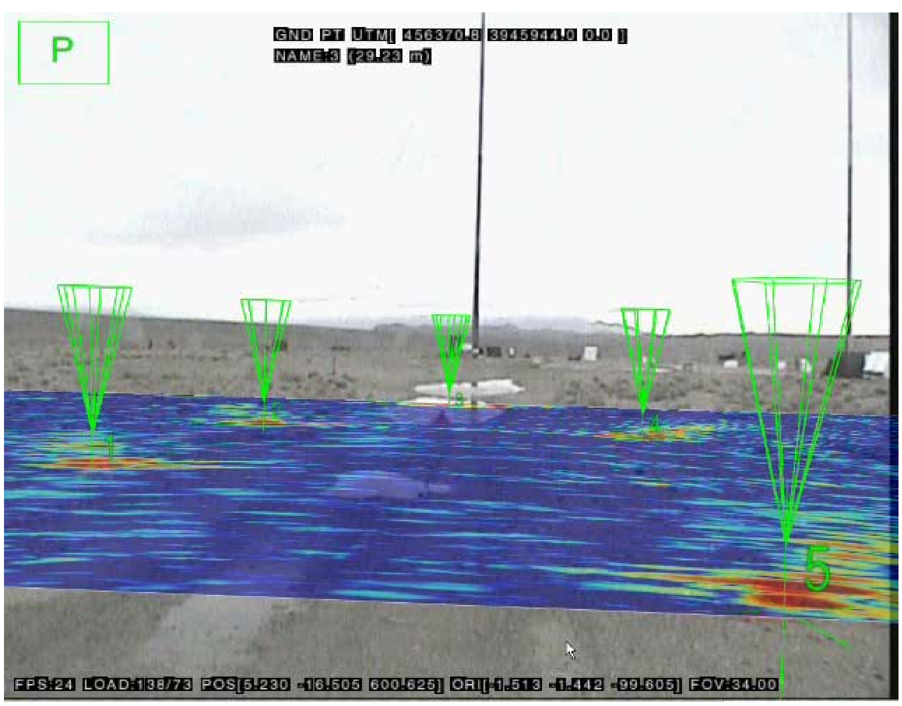


Figure 6: AR experiment result shows that SAR information is overlaid onto a live video stream.

where *R* is a 3x3 rotation matrix resulting from the arbitrary orientation of the camera, and *T* is a 3x1 vector of the translation of the camera lens with respect to the center of the geo-referenced coordinate system.

Equation (3) shows that a projection from 3D world to 2D image plane can be done if the coordinates, orientation (azimuth and elevation angles), and parameters (field of view, pixel size) of the camera are available. Figure 3 shows the integration of the AR system into the radar system. The major components of the AR systems are shown inside the dashed rectangle of Figure 3. The AR system receives the coordinates of the camera lens using the same GPS system of the radar. However, since the orientation of the camera is critical for the geo-referenced projection in the AR system, an inertial measurement unit (IMU) is integrated to provide this information. The PC communicates with the video camera and mount to control the desired orientation and field of view.

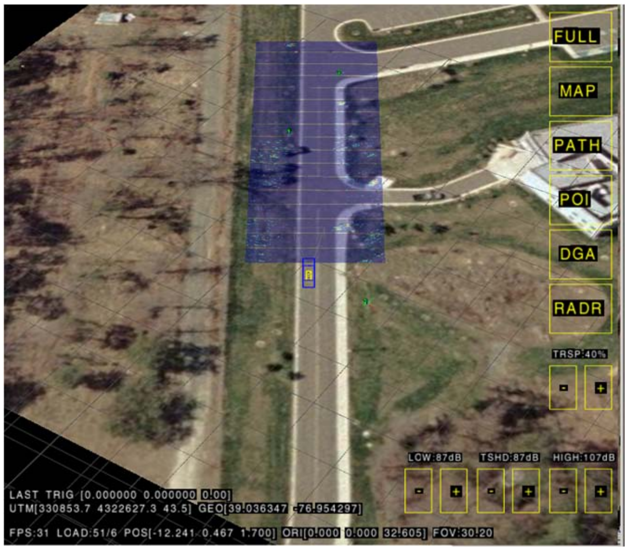


Figure 7: SAR image is overlaid on a digital photograph of an area.

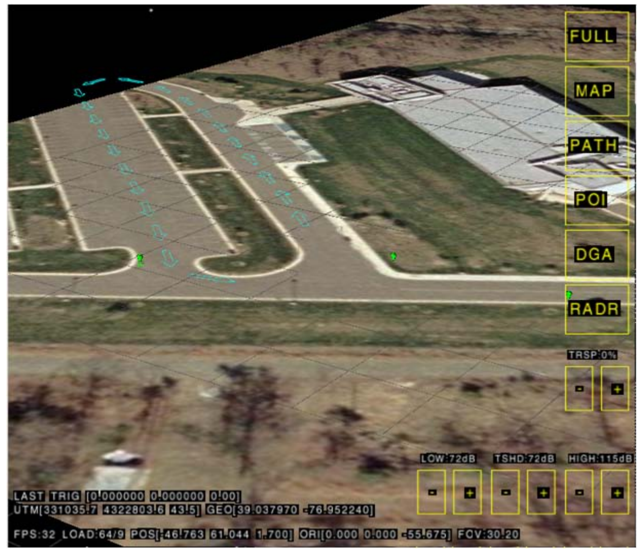


Figure 8: Radar path can be recorded and displayed for route planning.

Figure 6 shows the AR experiment result. In this experiment, five calibration targets (trihedrals) are in the scene. The radar collects data and forms SAR imagery of the scene. The geo-referenced SAR image and the surveyed locations of the calibration targets serve as inputs to the AR software (from ITT Industries), where the radar information is overlaid onto the live video stream from the camera. In this experiment, the UTM coordinates of the targets came from an independent surveyed source (not derived from SAR image) in order to demonstrate the registration capability of the AR system. These target locations are marked by the cone symbols. In practice, these markers would represent the likely target locations that the detection algorithm generates using SAR imagery. In the figure, the SAR image (formed using the ground plane) is overlaid on top of the video of the scene. The large responses from the SAR image (red color) are aligned with the actual calibration targets. Although the actual targets are not clearly visible in this figure, the transparency of the SAR image can be adjusted to allow the user to examine both the video and the SAR response of the targets. Using the registered information from both video and SAR images would help the user to quickly determine if an object is likely to be a real threat or just a benign object. The registration is performed in real-time, and adjusted with every movement and perspective of the camera. The user can click on any point-of-interest; the camera will automatically change its orientation and zoom in the area of interest.

Figure 9: User can report the coordinates of the danger areas.

Figures 7 to 9 illustrate other AR software features. In addition to the overlay of SAR information and live video, the software can also import digital overhead photographs from computer database. This allows the bird's-eye view of the area using both SAR imagery and overhead photographs. Figure 7 shows a SAR image that is overlaid on a digital photograph of an area. Although this is not an AR feature, it would allow an image analyst to examine and compare SAR image with the actual terrain features of the area. Figure 8 shows another feature of the software that overlays the path of the radar onto the display. This would help the user to follow a particular planning path. In radar change detection application, the user needs to follow the same route as previous runs. The radar detection software compares the SAR image of the current run versus a database of

SAR images from previous runs in order to detect any changes in the scene. Figure 9 shows another AR software feature. Once the user identifies a suspected area based on the information from the video and the SAR information, the software allows the user to generate a report by creating a polygon to represent the area using the mouse pointer.

4. Summary

Low-frequency UWB SAR offers the penetration capability to detect concealed targets. Although the information from SAR offers valuable information and complements other sensors that do not have the penetration capability, it is very difficult to comprehend the radar imagery and correlate the detection list from the radar with the objects in the real world. ARL has been collaborating with ITT Industries to customize the AR software to import SAR information. ARL conducted an experiment to demonstrate the feasibility of using an AR system to embed SAR information onto a live video stream of a real-world scene. The registration of the video stream and SAR information using the same geo-referenced coordinate system is performed in real-time and adjusted with every movement and perspective of the camera. Results from our experiment showed that the AR system successfully performed the registration with good accuracy. In the near future, ARL will incorporate a number of new capabilities/features to enhance the AR system: a) provide better user interface, b) record geo-referenced live video for automatic target detection development, and c) incorporate an IR camera.

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